BLURtooth: Exploiting Cross-Transport Key Derivation in Bluetooth Classic and Bluetooth Low Energy

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ABSTRACT

The Bluetooth standard specifies two incompatible wireless transports: Bluetooth Classic (BT) and Bluetooth Low Energy (BLE). The two transports have different security architectures and threat models and provide dedicated pairing protocols to establish long-term keys. Traditionally, two devices would have to pair over BT and BLE to use both securely. But in 2014, Bluetooth v4.2 addressed this usability issue by introducing *Cross-Transport Key Derivation (CTKD)* for BT and BLE. CTKD allows establishing BT and BLE pairing keys just by pairing over one transport. Despite the fact that CTKD crosses the security boundary between BT and BLE, the Bluetooth standard does not include CTKD in its threat model and does not provide a complete description of it.

To address these issues, we present a full characterization of CTKD obtained via reverse-engineering and a security analysis of CTKD. Based on our findings we introduce four standard-compliant attacks on CTKD breaking the strongest BT and BLE security modes. Our attacks are the first examples of cross-transport attacks for Bluetooth, as they enable breaking BT and BLE by targeting just one of the two. In contrast to prior standard-compliant attacks, our attacks do not require the attacker to be present when the victims are paring or establishing secure sessions, and their effect is persistent. We describe how the attacks can be used to impersonate and take over any device, man-in-the-middle secure sessions, and establish unintended sessions as an anonymous device. We refer to our attacks as *BLUR attacks*, as they blur the security boundary between BT and BLE. We provide a low-cost implementation of the BLUR attacks and we successfully evaluate them on 13 devices with 10 unique Bluetooth chips from popular vendors such as Cypress, Dell, Google, Lenovo, Samsung, and Sony. We discuss the root causes of the BLUR attacks and present effective countermeasures to fix them. We disclosed our findings and countermeasures to the Bluetooth SIG in May 2020 and received CVE-2020-15802.

1 INTRODUCTION

Bluetooth is a pervasive wireless technology used by billions of devices including mobile phones, laptops, headphones, cars, speakers, medical, and industrial appliances [11]. Bluetooth is specified in an open standard maintained by the Bluetooth special interest group (SIG), and its latest version is 5.2 [10]. The standard specifies two transports: Bluetooth Classic (BT) and Bluetooth Low Energy (BLE). BT is best suited for connection-oriented and high-throughput use cases, such as streaming audio and voice calls. While BLE is optimized for connection-less and very-low-power use cases such as localization and digital contact-tracing.

The Bluetooth standard defines different security architectures and threat models for BT [10, p. 947] and BLE [10, p. 1617]. Both transports provide pairing and secure session establishment protocols. Pairing enables the establishment of shared long term keys, and secure session establishment allows paired devices to create a secure channel through a (fresh) session key derived from the pairing key.

Traditionally, two devices would have to pair over BT *and* BLE to securely use both. However, pairing the same devices two times is considered user-unfriendly. To address this usability issue, Bluetooth v4.2 introduced *Cross-Transport Key Derivation (CTKD)* for BT and BLE in 2014. CTKD enables to pair two devices once, either on BT or BLE, and negotiate BT and BLE pairing keys without having to pair a second time [10, p. 1401]. For example, two devices can pair over BLE declaring CTKD support, agree on a BLE pairing key, and derive a BT pairing key without using BT. Alternatively, they can use CTKD from BT to derive BT and BLE pairing keys. All major Bluetooth software (e.g., Apple, Linux, Android, and Windows) and hardware providers (e.g., Cypress, Intel, Qualcomm, Broadcom, Apple, Sony, and Bose) support CTKD. Actually, Apple presented CTKD as a core and always-on feature to improve Bluetooth's usability [43].

Security-wise, CTKD has not received any attention from the research community and is only partially documented in the Bluetooth standard. In particular, CTKD is not part of the Bluetooth threat model and the standard does not provide a complete description of it. On the other hand, CTKD is a very interesting, yet-unexplored, attack surface, as it is a standard-compliant feature, is used together with the most secure modes of BT and BLE (i.e., Secure Connections), is crossing the security boundary between BT and BLE, and is transparent to the end-user.

In our work, we provide a complete description of CTKD obtained by merging the scattered and incomplete information about CTKD from the Bluetooth standard, and the result of reverse-engineering experiments conducted with actual devices. Based on our description, we performed a security evaluation of CTKD and we present four novel and standard-compliant attacks on CTKD. Our attacks are the first examples of *cross-transport* exploitation for Bluetooth, as they exploit BT and BLE only by targeting one transport.

The attacks are very effective as they can defeat all BT and BLE security mechanisms including Secure Simple Pairing (SSP), Secure Connections (SC), and strong associations. In contrast to prior standard-compliant attacks [2, 4, 5, 9, 19, 20, 34, 38, 39, 42, 44], our attacks do not require the attacker to be present during pairing and secure session establishment and they result in a persistent compromise of the victims.

Using our attacks we can reach several high-impact goals. In particular, they enable to impersonate and take over secure sessions from any BT or BLE device, man-in-the-middle BT and BLE secure sessions, and establish unintended BT and BLE sessions with a victim device while remaining anonymous and without breaking existing security bonds. We name our attacks *BLUR attacks*, as they blur the security boundary between BT and BLE.

We provide a low-cost implementation of the BLUR attack based on a Linux laptop and a Bluetooth development board. We show that the BLUR attacks are a real and standard-compliant threat by successfully conducting them on a diverse set of devices. In particular, we use our implementation to exploit 13 unique devices employing 10 unique Bluetooth chips from major hardware and software vendors (i.e., Broadcom, Cambridge Silicon Radio, Cypress, Google, Intel, Linux, Qualcomm, and Windows) implementing the most common Bluetooth versions supporting CTKD (i.e., Bluetooth versions 4.1, 4.2, 5.0, and 5.1).

To concretely address the presented attacks we infer their root causes by listing four cross-transport issues with the specification of CTKD. Then, we address those issues and the related BLUR attacks by proposing four effective countermeasures that can be implemented at the operating-system level (i.e., in the Bluetooth Host) with low effort. We summarize our contributions as follows:

- We reverse-engineered CTKD and performed its first security analysis. Based on that, we design four standard-compliant attacks on CTKD. The attacks break all BT and BLE security mechanisms including SSP, SC, and strong association, do not require the attacker to be present while the victims are pairing and establishing secure sessions, and their effect is persistent. Moreover, our attacks are the first examples of cross-transport attacks for Bluetooth as they exploit BT and BLE by targeting either of the two. Our attacks result in impersonation and take over of devices, MitM their secure sessions, and establishment of unintended sessions as an anonymous device. We name our attacks BLUR attacks, as they blur the security boundary between BT and BLE.
- We present a low-cost implementation of the BLUR attacks based on a Linux laptop and a Bluetooth development board. We use our implementation to confirm that actual devices are vulnerable to the BLUR attacks by successfully attacking 13 different devices employing 10 unique Bluetooth chips and covering the majority of Bluetooth versions compatible with CTKD (e.g., 4.1, 4.2, 5.0, and 5.1). We discuss four concrete attacks' root causes in the specification of CTKD and we provide four practical countermeasures to fix them.
- We disclosed our findings and countermeasures to the Bluetooth SIG in May 2020. The Bluetooth SIG acknowledged them and assigned CVE-2020-15802 to the BLUR attacks. In September 2020, the Bluetooth SIG released a security note about our report (without contacting us) at https://www.bluetooth.com/learn-about-bluetooth/bluetooth-technology/bluetooth-security/blurtooth/.

2 BACKGROUND

We now compare the most relevant features of BT and BLE. To provide precise technical descriptions we follow the *Bluetooth standard*'s master/slave terminology instead of more apt terms like leader/follower.

2.1 A Comparison of BT and BLE

BT and BLE are two wireless transports specified in the Bluetooth standard. These transports are incompatible (e.g.,they use different physical layers and link layers) and are designed to complement each other. BT is used for high-throughput and connection-oriented services, such as streaming audio and voice. BLE is used for very low-power and low-throughput services such as localization and monitoring. High-end devices, such as laptops, smartphones, headsets, and tablets, provide both BT and BLE, while low end devices such as mice, keyboards and wearables provide either BT or BLE.

BT and BLE have similar security mechanisms but different security architectures and threat models. In particular, both transports provide a pairing mechanism, named Secure Simple Pairing (SSP), to let two devices establish a shared long term key. BLE SSP is performed over the Security Manager Protocol (SMP) [10, p. 1666], while BT SSP uses the Link Manager Protocol (LMP) [10, p. 568]. During pairing, BLE allows negotiating the entropy of the long term key while BT does not. Additionally, BT and BLE provide a secure session establishment mechanism to establish a secure communication channel using a session key derived from the long-term pairing key. During session establishment, BT allows negotiating the entropy of the session key while the BLE session key inherits the entropy of the associated long term key.

BT and BLE use the same notion of pairable and discoverable states. If a device is pairable then it will accept pairing requests from other devices. If it is discoverable it will reveal its identity when other devices scan for nearby devices. Contrary to popular belief [41], a device can answer to a pairing request even if it is not discoverable. For example, if the user knows the MAC address of her pair of headphones she can complete BT or BLE pairing from her laptop without putting the headphones into discoverable mode.

BT and BLE provide a "Secure Connections" mode that uses FIPS compliant security primitives such as AES-CCM for authenticated encryption. Furthermore, they provide similar ways to protect against man-in-the-middle (MitM) attacks during the pairing phase defined in the standard as association procedures. Two examples of associations are Just Works that provides no MitM protection and Numeric Comparison that provides protection against a MitM by requiring user interaction during pairing (e.g., the user has to manually confirm that she sees the same numeric code on the pairing devices).

Both BT and BLE use a master-slave medium access protocol but define the master and slave roles differently. For BT, the master is the connection initiator, the slave is the connection responder, and roles can be switched dynamically by any party after a radio link is established. For BLE, the master and slave roles are fixed and cannot be switched. The BLE master (defined as central) acts as the connection initiator and the BLE slave (defined as peripheral) as the connection responder. High-end devices, such as laptops and smartphones, support both BLE master and BLE slave modes and are typically used as BLE masters, while low-end devices, such as fitness trackers and smartwatches, support only the BLE slave mode.

3 SECURITY ANALYSIS OF CTKD

In this section, we present our security analysis of CTKD. In particular, in Section 3.1 we describe what is publicly known about CTKD, and in Section 3.2 we complement it by reverse-engineering how CTKD works in practice for BT and BLE.

3.1 Public Information about CTKD

Before the introduction of CTKD, a user had to pair the same two devices over BT and BLE (i.e., two times) to use both transports securely. The Bluetooth SIG considered this procedure user-unfriendly and improved Bluetooth's usability by introducing CTKD for Bluetooth 4.2 in 2014. By using CTKD, two devices, pair only one time either over BT or BLE, and then can securely use both [10, p. 280]. For example, a pair of headsets and a laptop can pair over BLE, run CTKD to derive a second pairing key for BT (without the user having to put the headsets into BT pairing mode). Alternatively, the devices can pair over BT and run CTKD to generate the BLE pairing key. In both scenarios, after pairing once the headsets and the laptop can start secure sessions over BT and/or BLE.

The Bluetooth standard specifies that CTKD should be used only when a device supports Secure Connections mode for that specific transport [10, p. 1401]. Secure Connections is a security mode that was introduced both for BT and BLE to enhance their security primitives without affecting their security mechanisms. In particular, Secure Connections mandates the usage of FIPS-compliant algorithms such as AES-CCM, HMAC-SHA-256, and the ECDH on the P-256 curve [10, p. 269]. As a consequence, an attacker who can break CTKD can break BT and BLE's strongest security mode.

The Bluetooth standard also describes how CTKD derives pairing keys for BT and BLE [10, p. 1658]. CTKD uses the same key derivation function for BT and BLE, and the function takes as inputs a 128-bit (16-byte) key and two 4-byte strings and derives a 128-bit (16-byte) key. What changes between BT and BLE are the strings used as inputs. When CTKD is used to derive a BLE pairing key (K_{BLE}) from a BT pairing key (K_{BT}) then the key is derived using the "tmp2" and "brle" strings. In the other case, the derivation is performed using the "tmp1" and "lebr" strings. We note that the CTKD key derivation function is *deterministic*, as using CTKD on the same input key will always generate the same output key.

Despite being an optional feature, from the Internet and our experiments we can conclude that CTKD is supported by all major hardware and software vendors including Apple [43], Google [6], Cypress [13], Linux [12], Qualcomm [32], and Intel [21]. Actually, Apple presented it as a core and always-on Bluetooth feature during WWDC 2019.

3.2 Reverse Engineered Details on CTKD

The Bluetooth standard lacks a section about CTKD negotiation and usage for BT and BLE, but merely provides scattered information. Since knowing such information is essential to perform our security analysis, we reverse-engineered it. In this section we provide an high-level summary of the information that we extracted from our reverse-engineering process. To ease our description we abstract the protocols at a message level, where each message captures one or more packets sent over the air. Furthermore, we refer to the Bluetooth master as Alice, and the Bluetooth slave as Bob.

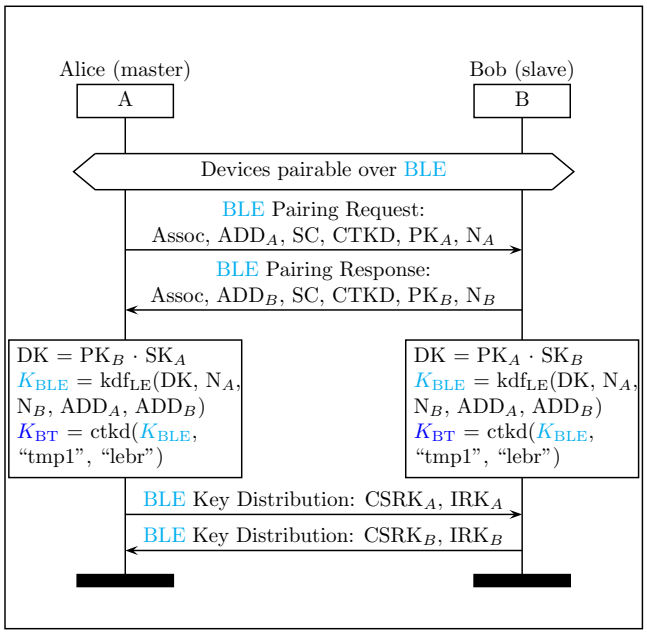

Figure 1: CTKD usage during BLE pairing. Alice and Bob negotiate SC and CTKD support during BLE pairing. Then, they compute the BLE pairing key and from that key, they derive the BT pairing key via CTKD (without exchanging any message over BT). Finally, they generate and exchange additional keys for BLE including signature (CSRK) and identity resolving (IRK) keys. After the protocol is completed Alice and Bob can establish secure sessions both for BT and BLE (without having to pair over BT).

CTKD from BLE. Figure 1 shows CTKD during BLE pairing. Alice and Bob are pairable BLE and discover each other using BLE's advertising and scanning features. Then, Alice and Bob negotiate specific capabilities using pairing request and response messages. The messages must contain Secure Connections (SC) and CTKD support, together with an association method (Assoc), a source BLE address (ADD), a public key (PK), and a nonce (N). Technically, CTKD support is declared by setting to one the Link Key bits of the Initiator and Responder key distribution SMP fields [10, p. 1680].

After exchanging the pairing messages, Alice and Bob compute a Diffie-Hellman shared secret (DH) using their remote public keys and local private keys (PK). The shared secret is then used to compute the BLE pairing key (K_{BLE}) using a dedicated BLE pairing key derivation function (kdf$_{LE}$). Then, Alice and Bob use CTKD's key derivation function (ctkd) to derive the BT pairing key (K_{BT}) from the BLE key and the static strings "tmp1" and "lebr". Finally, they establish a secure session over BLE and exchange additional keys such as CSRK, and IRK. Once the protocol is concluded, Alice and Bob can establish secure sessions over BT and BLE without having to pair over BT.

CTKD from BT. Figure 2 presents CTKD negotiation during BT pairing. Alice and Bob are pairable over BT and discover each other BT's inquiry mechanisms. Then, they exchange pairing request and

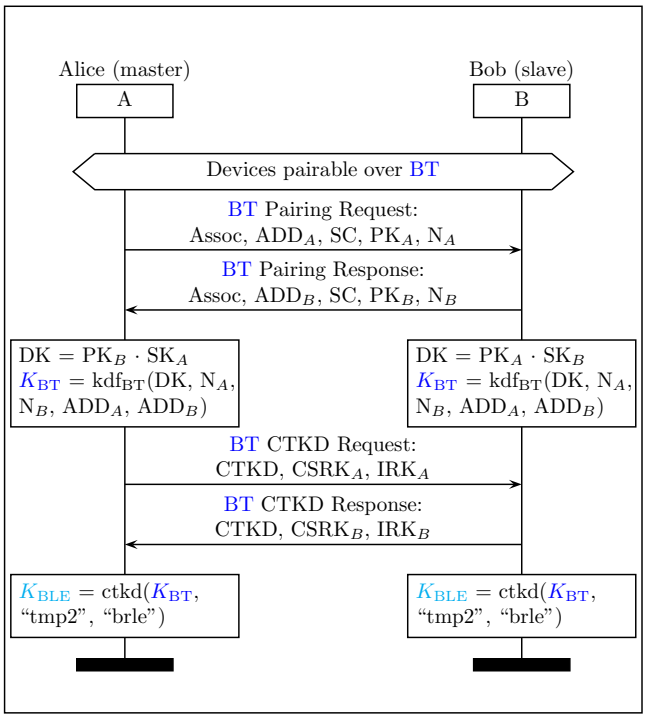

Figure 2: CTKD usage during BT pairing. Alice and Bob during BT pairing negotiate SC support. Then, they compute the BT pairing key, start a secure session over BT and send BT CTKD messages containing CTKD support and other keying material generated for BLE such as signature (CSRK) and identity resolving (IRK) keys. Notably, the CTKD request and response are encoded as BLE pairing request and response and tunneled over BT. Afterward, Alice and Bob derive the BLE pairing key, via CTKD (without exchanging any message over BLE). After the protocol is completed Alice and Bob can establish secure sessions both for BT and BLE (without having to pair over BLE).

response messages over BT to negotiate several BT capabilities (including SC), and to exchange their BT addresses, keys, and nonces. Unlike CTKD for BLE, CTKD is *not* negotiated with the BT pairing messages. But, Alice and Bob complete the BT pairing process by computing DH and using it together with their BT addresses and nonces to compute the BT pairing key (K_{BT}) through the BT pairing key derivation function (kdf_{BT}).

Then, CTKD negotiation takes place, as Alice and Bob establish a secure BT session and exchange two BT messages containing the CTKD flag and additional security material needed for BLE such as signature keys (CSRK) and identity resolving keys (IRK). These two messages are peculiar as they are formed by BLE pairing packets (SMP pairing request and response) sent over BT. This is the first example of BLE tunneling over BT that we observed, and the Bluetooth standard so far lacks any diagram or description of this behavior. Once CTKD is negotiated, Alice and Bob use it to derive the BLE pairing key (K_{BLE}) from the BT key and the static strings "tmp2" and "brle". After the protocol is completed, Alice and Bob can start BT and BLE secure sessions without having to pair over BLE.

Figure 3: CTKD life cycle has three phases: Discovery (to exchange features), Initialization (to agree on a pairing key and, through CTKD, create a pairing key for the other transport), and Communication (to establish secure sessions on BT and/or BLE).

CTKD life cycle. By combining all the information acquired from public documents, reverse-engineering implementations, and our experiments, we represent the CTKD life cycle for BT and BLE in three phases: Discovery, Initialization, and Communication. Figure 3 shows the life cycle assuming that Alice is a laptop and Bob a pair of headphones. During Discovery, Alice and Bob are pairable on the relevant transport and discover each other. During Initialization, Alice and Bob negotiate SC and CTKD, use one transport (either BT or BLE) to establish a pairing key, and then derive a pairing key for the other transport using CTKD without having to pair a second time. Finally, during Communication the devices are free to establish BT and BLE secure sessions using their shared pairing keys. Each session uses a fresh session key derived from the pairing key and session nonces.

4 BLUR ATTACKS VIA CTKD

We now present our threat model and the design of four novel and standard-compliant attacks for Bluetooth. Our attacks are the first samples of *cross-transport* exploitation for Bluetooth, as they are capable of exploiting BT and BLE just by targeting either of the two. Our attacks are stealthy as CTKD is transparent to the users, and do not require a strong attacker model as the attacker does not have to be present when the victims are pairing or establishing a secure session. As our attacks are blurring the security boundary between BT and BLE, we name them the *BLUR attacks*.

4.1 System Model

Our system model considers two victims, Alice and Bob, who can securely communicate over BT and BLE. The victims support CTKD, and are using the most secure BT and BLE modes, namely, SC and strong association (e.g., Numeric Comparison if both have the necessary IO). This setup should protect the victims against device impersonation, traffic eavesdropping, and active man-in-the-middle attacks on BT and BLE [10, p. 269]. Without loss of generality, we assume that Alice is the master and Bob is the slave.

Regarding the notation, we indicate a BT pairing key with K_{BT}, a BT session key with SK_{BT}, a BLE pairing key with K_{BLE}, a BLE session key with SK_{BLE}. We indicate a Bluetooth address with ADD, a public key with PK, a private key with SK, a shared Diffie-Hellman secret with DK, a nonce with N, and a message authentication code with MAC.

4.2 Attacker Model and Goals

Our attacker model considers Charlie, a remote attacker who is in Bluetooth radio range with the victims. The attacker aims to compromise the secure BT and BLE sessions between the victims without tampering with their devices. The attacker's knowledge is limited to what the victims advertise over the air, e.g., full or partial Bluetooth addresses, Bluetooth names, authentication requirements, IO capabilities, and device classes.

The attacker does not know any BT or BLE key shared between the victims, does not have to be present when the victims pair or negotiate a secure session. The attacker can scan and discover devices, send pairing requests and responses, use CTKD, propose weak association mechanisms (e.g., Just Works), and dissect and craft Bluetooth packets.

The attacker has four goals. The first one is to impersonate Alice (to Bob) and potentially take over Alice's secure sessions. The second goal is to impersonate Bob (to Alice) and also take over Bob's secure sessions. By take over, we mean that after the attack the security bond between the two victims is broken. We note that, Alice and Bob' impersonations are different goals as they require different impersonation techniques (i.e., master and slave impersonations).

The attacker's third objective is to establish a man-in-the-middle position in a secure session between two victims and requires combining and synchronizing Alice and Bob's impersonation attacks. The fourth objective is to establish unintended and possibly stealthy sessions with Alice or Bob as an arbitrary device, without taking over a session and breaking existing security bonds. An unintended session enables the attacker to access a much broader attack surface than the one exposed in a connection-less scenario.

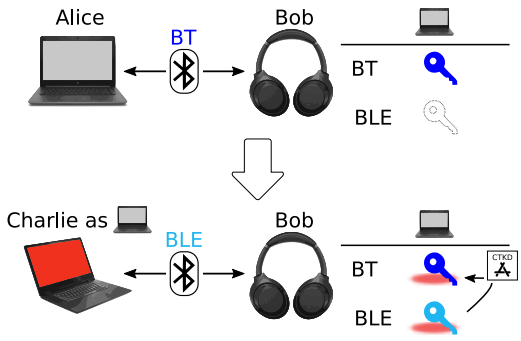

Figure 4: Attack strategy. Alice and Bob are paired over BT and run a secure BT session. Charlie pairs with Bob as Alice over BLE declaring CTKD support. Then Charlie agrees upon a BLE pairing key with Bob, and, via CTKD, tricks Bob into overwriting Alice's BT pairing key. As a result, Charlie can establish BT and BLE sessions with Bob as Alice, and takes over the real Alice who can no longer connect to Bob. Using a similar strategy, Charlie can also impersonate Bob to Alice, man-in-the-middle Alice and Bob, and establish unintended BT and BLE sessions as an arbitrary device.

4.3 Attack Strategy

We now describe our attack strategy using Alice's impersonation as a reference example and with the help of Figure 4. Let us assume that Alice is a laptop and Bob is a pair of headphones and the victims are already paired and they are running a secure BT session. Since the victims support CTKD, they are also pairable over BLE, even if the transport is not currently in use. Charlie sends a BLE pairing request to Bob pretending to be Alice and claiming CTKD support. Bob, even if running a BT session with Alice, has to answer to Charlie with a BLE pairing response as Charlie's message is compliant with the Bluetooth standard.

Then, Charlie (as Alice) and Bob agree on a BLE pairing key and, via CTKD, generate a new BT pairing key that *overwrites* Alice's key in Bob's BT key store. In doing so, Charlie, wins two prizes with one shot, as he takes over Alice's BT and BLE sessions with Bob. In other words, Alice can no longer connect to Bob as she does not know the BT and BLE pairing keys (overwritten by the attacker). Furthermore, Charlie also overwrites other security keys that are distributed during pairing, including CSRK (signature key) and IRK (MAC randomization key). We note that the overwrite trick is transparent to the end user as the standard does not mandate to notify the user about CTKD, and works even if Alice and Bob are sharing BT *and* BLE pairing keys before the attack takes place.

Following a similar strategy, Charlie can impersonate Bob to Alice, man-in-the-middle them, and create unintended sessions as an arbitrary device with a victim. We note that our attack strategy is effective because the Bluetooth standard does not enforce important security properties at the boundary between BT and BLE and does not address all cross-transport threats in its threat model (see Section 7.1 for more details). In the remaining of this section, we describe the technical details of the four BLUR attacks.

4.4 Impersonation Attacks

Master impersonation. Charlie impersonates Alice and takes over her BT and BLE sessions with Bob as in Figure 5. Bob is already paired with Alice, and can run a BT session with her while Alice's impersonation takes place. Notably, Bob must be pairable over BT and BLE to support CTKD from BT and BLE. Charlie takes advantage of that and sends a BLE pairing request as Alice by using Alice's Bluetooth address (ADD_A), Just Works (JW) association to avoid user interaction while pairing, his public key (PK_C), and CTKD support.

As Charlie's BLE pairing request is standard-compliant, Bob sends back a BLE pairing response believing that Alice wants to pair (or re-pair) over BLE using CTKD. Then, Charlie and Bob compute K_{BLE}, derive K_{BT} via CTKD, and exchange additional BLE key material (e.g., CSRK, IRK) over a BLE secure session. After the master impersonation attack is completed Charlie takes over Alice's BT and BLE sessions by tricking Bob into overwriting Alice's BT and BLE keys with his ones.

Slave impersonation. Charlie impersonates Bob and takes over his BT and BLE sessions with Alice as in Figure 6. Alice and Bob have already paired and can run a BLE secure session while the impersonation takes place. Alice has to be pairable over BT and BLE to provide CTKD support from both transports, and Charlie takes advantage of that by sending a BT pairing request to Alice as

Bob using Bob's address (ADD_B), Just Works (JW), and his public key (PK_C). Charlie's paring request is still standard-compliant even if Charlie is supposed to be the slave as BT, unlike BLE, enables a slave to switch to a master role before sending a pairing request.

Alice answers with a BT pairing response believing that Bob wants to re-pair over BT, and the two agree on K_{BT}. Then, Charlie starts a secure BT session and sends a tunneled BLE pairing request to Alice still pretending to be Bob. The BLE pairing request includes CTKD support and Charlie's signature and MAC randomization BLE keys ($CSRK_C$, IRK_C). Alice answers with a BLE pairing response tunneled over BT and the two derives K_{BLE} via CTKD. Once the slave impersonation attack is completed, Charlie takes over Bob's BT and BLE sessions by tricking Alice into overwriting Bob's BT and BLE keys with his ones.

Man-in-the-middle. Charlie can conveniently combine the described master and slave attacks to launch a cross-transport man-in-the-middle attack as shown in Figure 7. If Alice and Bob are running a BLE session, Charlie starts with the slave impersonation attack presenting to Alice as Bob over BT. Otherwise, he launches a master impersonation attack by targeting Bob as Alice over BLE. After the first impersonation attack, the impersonated victim is taken over and disconnects from the other victim. Then, Charlie targets the impersonated victim with a second impersonation attack and establishes a MitM position between the two victims. As a result, Charlie controls all BT and BLE secure sessions between Alice and Bob.

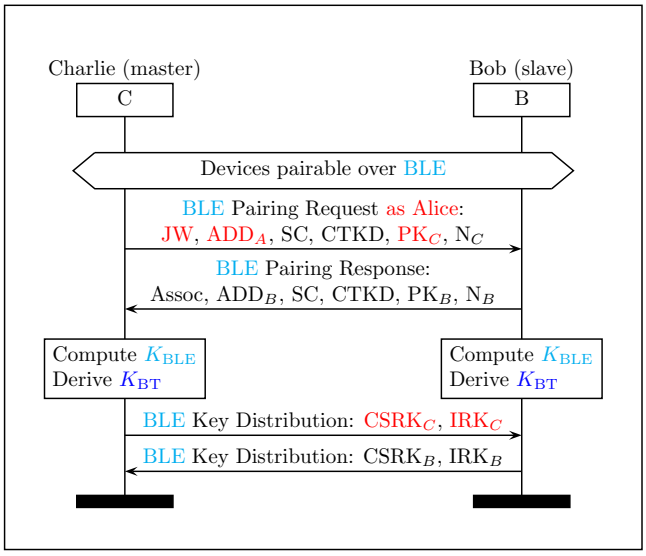

Figure 5: BLUR master impersonation attack. Charlie sends a BLE pairing request with Alice's address (ADD_A) including Just Works (JW) association to avoid user interaction, CTKD, and his public key (PK_C). Bob answers with a BLE pairing response thinking that he is talking to Alice. The attacker and the victim agree on K_{BLE}, and derive K_{BT}, via CTKD and complete BLE paring by generating and distributing more keys over a secure BLE session. As a result of the master impersonation attack, Charlie tricks Bob into overwriting Alice's keys with his ones and takes over Alice who can no longer connect back to Bob.

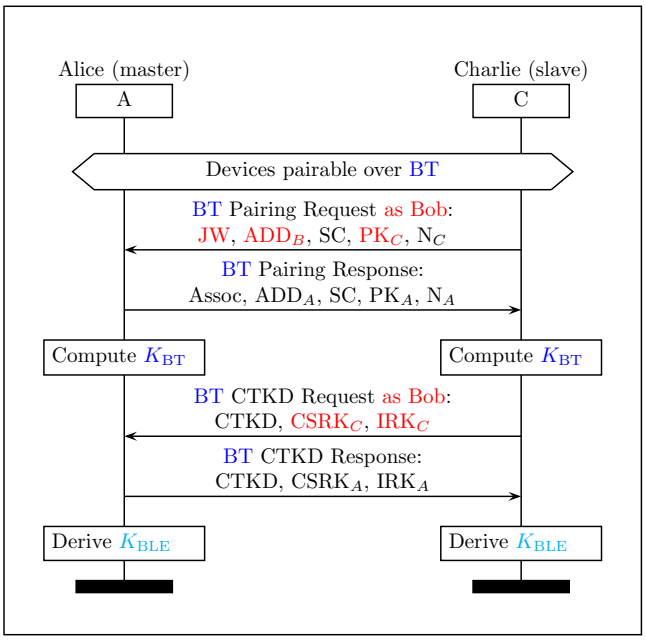

Figure 6: BLUR slave impersonation attack. Charlie sends a BT pairing request with Bob's address (ADD_B) including Just Works (JW) association to avoid user interaction, and his public key (PK_C). The pairing request is valid as BT enables to dynamically switch from slave to master before sending a pairing request. Alice answers with a BT pairing response believing that she is talking to Bob. The attacker and the victim establish K_{BT}, negotiate CTKD and exchange additional keying material for BLE with a BT CTKD request and response messages, and derive K_{BLE}. As a result of the slave impersonation attack, Charlie tricks Alice into overwriting Bob's keys with his ones and takes over Bob who can no longer connect back to Alice.

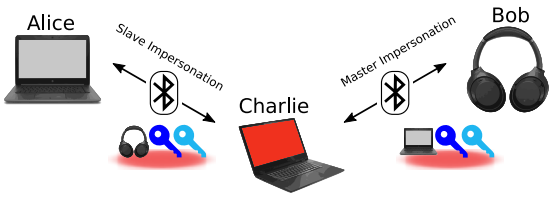

Figure 7: BLUR man-in-the-middle attack. Charlie combines the master and slave impersonation attacks presented so far to establish a man-in-the-middle position between Alice and Bob both on BT and BLE.

4.5 Unintended Session Attacks

So far we described how to exploit CTKD to impersonate any Bluetooth device, however, the attacker can also take advantage of CTKD to establish unintended BT and BLE sessions with a victim

as an anonymous device with arbitrary capabilities. Unintended sessions are interesting because they expose a larger attack surface than a setup where the attacker can only send scanning or advertising packets to a victim (i.e., when the victim does not trust the attacker). For example, by establishing unintended sessions, the attacker can enumerate all BT and BLE services supported by the victim and exploit a remote code execution vulnerability that would not have been exploitable without a secure session. Concurrently, these attacks are more difficult to spot than impersonation ones as they do not require to take over existing secure bonds (i.e., they do not require to overwrite keys).

Let us see how an unintended session attack works in a scenario where Alice and Bob are already paired and are running a secure BT session (see Figure 8). As in the impersonation attack scenario, Alice and Bob must also be pairable over BLE to support CTKD. Charlie targets Bob by sending a BLE pairing request using a random Bluetooth address, CTKD support, and Just Works for association. Bob answers to Charlie's request and the two negotiate K_{BLE}, and derive K_{BT} via CTKD. Now, Charlie can establish secure but unintended BT and BLE sessions with Bob without breaking Bob's existing sessions (e.g., with Alice) and by using an anonymous identity and arbitrary capabilities. Using a similar strategy, Charlie can reach the same goals targeting Alice.

5 IMPLEMENTATION

In this section we describe our attack scenario, our implementation of a custom attack device to perform the BLUR attacks and our re-implementation of CTKD's key derivation function. We will fully open-source both the attack and our CTKD key derivation functionality.

5.1 Attack Scenario

Our attack scenario follows the example in Figure 9 and includes two victims, Alice (master) and Bob (slave). Alice is represented by a 7th generation ThinkPad X1 laptop and Bob by a pair of Sony WH-CH700N headphones. The attacker (Charlie) uses a CYW920819 development board [14] and a 3rd generation ThinkPad X1 laptop as an attack device. The implementation of the attack device is presented in Section 5.2. In our evaluation, presented in Section 6, we use the same attack scenario to attack other victim devices.

Table 1 summarizes the most relevant features of Alice, Bob, and Charlie. Alice and Bob have an Intel Bluetooth chip, while Bob has a Cambridge Silicon Radio (CSR) one. Alice, Bob, and Charlie support respectively Bluetooth 5.1, 4.1, and 5.0. Alice and Charlie support Secure Connections both on the Host and the Controller, while Bob only on the Controller. All devices support BT, BLE, and CTKD. Regarding pairing association methods, the laptops support Numeric Comparison, while the headsets only support Just Works as they lack a display.

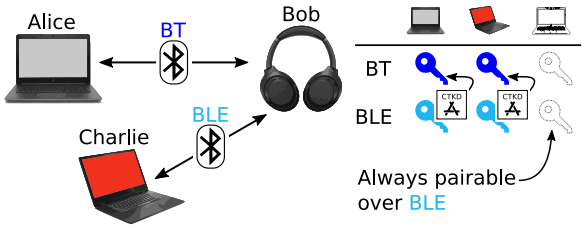

Figure 8: BLUR unintended sessions attack. Charlie can take advantage of CTKD to establish unintended BT and BLE session with Bob as a random device with arbitrary capabilities. The same can happen if Charlie targets Alice.

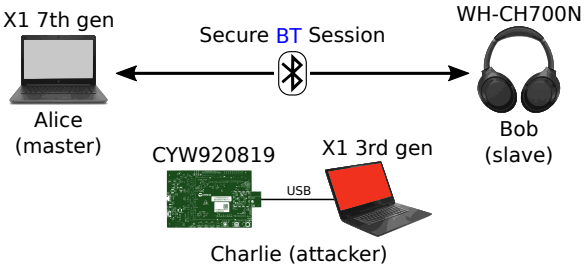

Figure 9: BLUR Attack Scenario. Alice (master) is a ThinkPad X1 7th gen, Bob (slave) is a pair of Sony WH-CH700N headphones and Charlie (attacker) is a CYW920819 board connected via USB to a ThinkPad X1 3rd gen. Alice and Bob have paired in absence of Charlie, and are running a secure BT session.

	Alice	Bob	Charlie
Device(s)	X1 7th gen	WH-CH700N	X1 3rd gen / CYW920819
Radio Chip	Intel	CSR	Intel / Cypress
Subversion	256	12942	256 / 8716
Version	5.1	4.1	5.0
Name	x7	WH-CH700N	x1
ADD	Redacted	Redacted	Redacted
Class	0x1c010c	0x0	0x0
BT SC	True	Only Controller	True
BT AuthReq	0x03	0x02	0x03
BLE SC	True	True	True
BLE AuthReq	0x2d	0x09	0x2d
CTKD	True	True	True
h7	True	False	True
Role	Master	Slave	Master
IO	Display	No IO	Display
Association	Numeric C.	Just Works	Numeric C.
Pairable	True	True	True

Table 1: Relevant Bluetooth features for Alice, Bob, and Charlie. We redact the devices' Bluetooth addresses for privacy reasons.

5.2 Custom Attack Device

To conduct our attacks we developed a custom attack device making use of a CYW920819 development board connected to a Linux laptop

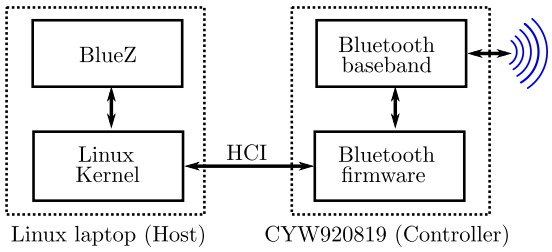

Figure 10: Attack Device Block Diagram. The attack device is composed of Linux laptop (Host) and a CYW920819 development board (Controller) connected via USB and communicating using the Host Controller Interface (HCI) protocol.

(see Figure 10). Both devices BT, BLE, SC, and CTKD. Using standard laptops, smartphones or dongles is not sufficient to implement the BLUR attacks, as they do not allow to modify all device's identifiers (e.g., BT and BLE address) and all devices' capabilities advertised over the air (e.g., firmware and controller versions). A software-defined radio (SDR) is also out of scope because there is no open-source BT/BLE SDR stack currently available.

Instead, with our attack device, we can program our development board (Bluetooth Controller) to impersonate any BT/BLE device, we can patch its closed-source firmware to control both BT LMP and BLE LL link layer packets. Moreover, we can alter the laptop's BT and BLE kernel and user-space code to set Bluetooth Host-specific configuration bits such as negotiating CKTD and Just Works. We now describe in detail how we modify the attack device's Host and Controller components.

Host modifications. For the host, we use standard Linux tools to configure an Bluetooth interface (e.g., `hciconfig`), and to discover and pair with a device (e.g., `bluetoothctl`, `hcitool` and `btmgmt`). In particular, `btmgmt` was very useful as it provides handy low-level commands. For example, it includes commands to toggle BT, BLE, SC, scanning, and advertising. Moreover, it allows to easily send custom pairing requests on BT and BLE and to set the related association (e.g., Just Works).

Furthermore, we configured our host to get all link-layer packets sent and received by the controller. This is handy as it enables to monitor both HCI and link-layer packets directly from the host (e.g., using Wireshark). To activate link-layer packet forwarding, we sent a proprietary Cypress HCI command from the host to the controller that switches on an undocumented diagnostic mode in the controller. Then, we added extra C code to the Linux kernel to parse those special HCI packets in the host.

Controller modifications. We modified the controller by dynamically patching the development board Bluetooth firmware using a Cypress proprietary mechanisms. To patch the firmware we had to extract it from the board and statically reverse-engineer its relevant parts. In particular, to extract the firmware we used a proprietary HCI command to read and save a runtime RAM snapshot from the board's SoC. We use the memory maps that we extracted from the board's SDK to extract the memory segments from the snapshot (e.g., ROM, RAM, and the scratchpad). As expected, the firmware was in the ROM segment and was a stripped ARM binary containing 16-bit Thumb instructions.

To reverse-engineer the firmware, we loaded the ROM, RAM, and scratchpad in Ghidra and statically analyzed them. In our first pass, we isolated the libc functions (e.g., `malloc` and `calloc`) by looking at the signatures and the code patterns of the functions that are called the most. Then, we found the firmware debugging symbols hidden in the board's SDK and loaded them into Ghidra. Using these symbols we isolated functions and data structures relevant to the BLUR attacks. Then, we wrote ARM Thumb assembly patches to change their behaviors and we apply those patches at runtime using internalblue [28], an open-source toolkit to manage several Bluetooth devices including our board. Our set of patches allows transforming our board in whatever device we want by changing its identifiers including addresses, names, and capabilities,

5.3 CTKD Key Derivation Function

We implemented CTKD's key derivation function, following its specification in the Bluetooth standard [10, p. 1401]. We used our implementation to check that the keys that we observed during our experiments were correctly derived, yet, it is not required to conduct the BLUR attacks. Our implementation is written in Python 3 and uses the PyCA cryptographic module [7]. We tested it against the CTKD test vectors in the standard [10, p. 1721]. We now describe its technical details.

$$K_{BLE} = \begin{cases} f\left(f\left(tmp2, K_{BT}\right), brle\right) & \text{if h7 is supported} \\ f\left(f\left(K_{BT}, tmp2\right), brle\right) & \text{otherwise} \end{cases}$$

We implemented CTKD's key derivation for BT deriving and following the equation above. The key derivation computes K_{BLE} using a function $f(a, b)$ that corresponds to AES-CMAC$(key, plaintext)$. If both pairing devices declare h7 support, then K_{BLE} is computed using the equation at the top otherwise the one at the bottom. h7 is a key conversion function defined in the Bluetooth standard and is negotiated during pairing using AuthReq [10, p. 1634].

$$K_{BT} = \begin{cases} f\left(f\left(tmp1, K_{BLE}\right), lebr\right) & \text{if h7 is supported} \\ f\left(f\left(K_{BLE}, tmp1\right), lebr\right) & \text{otherwise} \end{cases}$$

We also implemented CTKD's key derivation for BLE deriving and following the equation above. In this case the derived key is K_{BT}. The equations' logic is identical to the one explained for BT. What changes are the input parameters. In particular, the computation uses as inputs: K_{BLE}, "tmp1", and "lebr".

6 EVALUATION

In this section we present how we conducted the BLUR attacks and our evaluation results on 13 devices using 10 unique Bluetooth chips (see Table 2). Our evaluation exploit different device types (e.g., laptops, smartphones, headphones, and development boards), manufacturers (e.g., Samsung, Dell, Google, Lenovo, and Sony), operating systems (e.g., Android, Windows, Linux, and proprietary OSes), and Bluetooth chip (e.g., Broadcom, CSR, Cypress, Intel, Qualcomm, and Samsung).

Device			Chip		Bluetooth	BLUR Attack			
Producer	Model	OS	Producer	Model	Version	Role	MI/SI	MitM	US
Cypress	CYW920819EVB-02	Proprietary	Cypress	CYW20819	5.0	Slave	✓	✓	✓
Dell	Latitude 7390	Win 10 PRO	Intel	8265	4.2	Slave	✓	✓	✓
Google	Pixel 2	Android	Qualcomm	SDM835	5.0	Slave	✓	✓	✓
Lenovo	X1 (3rd gen)	Linux	Intel	7265	4.2	Slave	✓	✓	✓
Lenovo	X1 (7th gen)	Linux	Intel	9560	5.1	Slave	✓	✓	✓
Samsung	Galaxy A40	Android	Samsung	Exynos 7904	5.0	Slave	✓	✓	✓
Samsung	Galaxy A51	Android	Samsung	Exynos 9611	5.0	Slave	✓	✓	✓
Samsung	Galaxy A90	Android	Qualcomm	SDM855	5.0	Slave	✓	✓	✓
Samsung	Galaxy S10	Android	Broadcom	BCM4375	5.0	Slave	✓	✓	✓
Samsung	Galaxy S10e	Android	Broadcom	BCM4375	5.0	Slave	✓	✓	✓
Samsung	Galaxy S20	Android	Broadcom	BCM4375	5.0	Slave	✓	✓	✓
Sony	WH-1000XM3	Proprietary	CSR	12414	4.2	Master	✓	✓	✓
Sony	WH-CH700N	Proprietary	CSR	12942	4.1†	Master	✓	✓	✓

† CTKD functionality was backported by the vendor to Bluetooth 4.1 for this device.

Table 2: BLUR attacks evaluation results. The first three columns show the device's producer, model, and OS. The next two columns state the Bluetooth chip's produce and model. The sixth column tells the Bluetooth version of the target device. The seventh column indicates the attacker's role (e.g., if Slave then the attacker is the slave and targets a master). Finally, the last three columns contain a check mark (✓) if a device is vulnerable to the relevant BLUR attack. We group master and slave impersonation attacks in the same column (MI/SI) as each victim can only have one role. All the devices that we tested are vulnerable.

6.1 Conducting the Attacks

The BLUR attacks, presented in Section 4, include master impersonation, slave impersonation, man-in-the-middle, and unintended session attacks. In the next paragraphs, we describe how we conducted them using our custom attack device described in Section 5.2.

Laptop (master) BLUR impersonation attack. To impersonate the laptop, we patch our attack device to clone the laptop's Bluetooth features (including Bluetooth address, Bluetooth name, device class, SC, and CTKD support). Then, we send a BLE pairing request from the attack device to the headphones declaring CTKD and Just Works support. The malicious BLE pairing request is sent using `btmgmt`'s text-based user interface (TUI). The headphones accept the pairing request, and the devices agree on K_{BLE}, derive K_{BT} via CTKD and establish a secure BLE session. Then, the headphones terminate the BT session with the impersonated laptop and establish a secure BT session with the attack device. The impersonated laptop cannot connect back with the headphones as it does not possess the correct pairing keys overwritten by the attacker.

Headphones (slave) BLUR impersonation attack. To impersonate the headphones, we patch our attack device to clone the headphones' Bluetooth features. Then, we send a BT pairing request from the attack device to the laptop declaring CTKD and Just Works support using `btmgmt`'s TUI. The laptop accepts to pair over BT, and the devices agree on K_{BT}, negotiate CTKD, derive K_{BLE}via CTKD, and establish a secure session over BT. The impersonated headphones cannot connect to the laptop as they do not own the correct paring keys.

To optimize the evaluation of the master and slave impersonation attacks, we used the attack device both as the attacker and the impersonated victim. For example, in a master impersonation attack we pair the attack device with the slave victim device, we disconnect them, we "forget" the victim device on the attack device and we run the master impersonation attack from the attack device. This setup is efficient because it allows us to quickly test many slave victims. For the slave impersonation, we use the same procedure to test our master victims.

BLUR Man-in-the-middle attack. By using our BLUR implementation with two development boards connected to the same attack laptop, we can impersonate the laptop and the headphones at the same time, and man-in-the-middle them. In particular, we run the laptop (master) impersonation attack first, and then the headphone (slave) impersonation attack. As a result, the attack device positions itself in the middle between the victims.

BLUR Unintended sessions attack. For the unintended session attack, we patched our attack device to look like an unknown device to the current victim. If the victim is a master, we run the same steps used in the slave impersonation attack otherwise we use the master impersonation attack's steps. In both cases, the attacker creates unwanted but trusted bonds with a victim and can establish secure sessions over BT and BLE with the victim.

6.2 Evaluation Results

We evaluated the BLUR attacks against 13 unique devices (employing 10 unique Bluetooth chips) and our results are summarized

in Table 2. The first six columns indicate the device's producer, model name, operating system, chip manufacturer, chip model, and Bluetooth version. The seventh column contains either Slave if the device was tested against a slave impersonation attack, or Master if the device was tested against a master impersonation attack. The table's last three columns contain a check mark (✓) if a device is vulnerable to master or slave impersonation attack (MI/SI), man-in-the-middle attack (MitM), or unintended session (US) attack.

From Table 2 we can draw several significant conclusions. Firstly, it shows that the BLUR attacks are practical as all devices that we tested are vulnerable. Secondly, the table demonstrates that all the Bluetooth versions that we tested are vulnerable, i.e., Bluetooth versions 4.1, 4.2, 5.0, and 5.1. Finally, the table confirms that the BLUR attacks are standard-compliant as they work regardless of device-specific implementation details.

7 DISCUSSION

In this section, we describe four issues affecting CTKD's specification that we extrapolated from the BLUR attacks. These issues are standard-compliant and represent the root causes of the BLUR attacks. Furthermore, we propose four effective countermeasures to address the BLUR attacks. Finally, we discuss the main lessons learned.

7.1 Cross-Transport Issues with CTKD

We isolated four cross-transport issues (CTI) with the specification of CTKD. All CTI are related to the cross-transport nature of CTKD, i.e., the fact that CTKD bridges BT and BLE security domains without properly enforcing certain aspects. We now describe each of them in detail.

CTI 1: Role Asymmetry. BT and BLE define their master and slave roles differently. In particular, BT enables to switch roles dynamically on demand, while for BLE the roles are fixed. The attacker takes advantage of this CTI by acting as a master for BT and a slave for BLE. For example, in the slave impersonation attack, the attacker can send a BT pairing request, when the victim would expect to receive only BT responses.

CTI 2: Association Asymmetry. The Bluetooth standard does not mandate to enforce the same association mechanism for BT and BLE. An attacker can take advantage of this issue to use a weak association method on one transport when the other is expecting to use a stronger association mechanisms. For example, in the master impersonation attack even if the victims have paired over BT with strong association, the attacker can pair over BLE with weak association (i.e., Just Work) and impersonate a device.

CTI 3: Key (Over)write. With CTKD the Bluetooth standard introduces a new attack primitive, that is, cross-transport key (over)writing. The attacker can use such primitive to overwrite trusted pairing keys and distribute new BT and BLE keys. All the presented attacks take advantage of this issue.

CTI 4: Pairing States. With CTKD the Bluetooth standard enables more ways to pair devices. The attacker can take advantage of this issue to target the transport not currently in use by the victims. For example, in the master impersonation attack, the attacker sends a pairing request over BLE while the victims are using BT.

7.2 Countermeasures

We now present four countermeasures to mitigate the BLUR attacks presented in Section 4. In particular, the first three mitigations defeat the BLUR impersonation and MitM-attacks, while the unintended session attacks are prevented by deploying the fourth mitigation. The countermeasures are also addressing the CTI issues described in Section 7.1, and can be implemented on the device's Bluetooth Host (OS) by storing and checking metadata about its state and list of trusted devices. We argue that the Bluetooth Host is the natural place to store this new metadata in addition to other metadata such as long term keys.

Align BT and BLE roles. To fix role asymmetries between BT and BLE, a device should store the role that the remote device used while pairing and enforce it across re-pairings. In case of a role mismatch, the device should abort pairing.

Enforce strong association mechanisms. To align association methods between BT and BLE pairings, a device should keep track of the strongest association mechanism used while pairing either on BT or BLE and enforce it for subsequent (re-)pairings. If a weaker mechanism than the one stored is proposed, pairing should be aborted.

Disable CTKD key overwrites. CTKD allows (over)writing security keys across BT and BLE. To fix key overwrites via CTKD, a device should disallow to update a trusted key via CTKD when a paired device wants to re-pair. For example, re-pairing over BT should not overwrite a BLE pairing key that was securely established in the past.

Disable pairing when not needed. To prevent an attacker from pairing with a victim device in unexpected ways, a device should automatically stop being pairable on a transport that is not currently in use. For example, a pair of headphones who are running a secure session over BT with a laptop should not answer pairing requests over BLE unless the user explicitly set the headphones in pairing mode.

7.3 Lessons Learned

There are several lessons that we learned while analyzing CTKD and developing the BLUR attacks. We report them in the hope that they will be useful for protocol designers who are dealing with cross-transport features and related security issues.

Cross-transport mechanisms need a cross-transport threat model. Security mechanisms that cross the security boundary between two technologies should be designed and tested against a cross-transport threat model. For example, the Bluetooth standard should include in its threat model an attacker who wants to exploit BT from BLE and vice versa, rather than considering only attackers focused either on BT or BLE.

Security mechanisms used to cross a security boundary should provide the same security guarantees. Cross-transport mechanisms should be designed such that the mechanisms used to cross the

			Attack				
Year	Paper	Target	Phase	C I A K	SC/SCO	Persistent	Note
Attacks on BT							
2016	Albazrqaoe et al. [1]	Standard	Any	◐○○○	x	-	BlueEar Sniffer
2017	Seri et al. [35]	Impl.	Pairing	●●●○	NA	✓	BlueBorne
2018	Sun et al. [38]	Standard	Pairing	●●●○	✓	-	Passkey (MitM)
2018	Biham et al. [9]	Impl.	Pairing	●●●◐	NA	✓	Fixed Coordinate Invalid Curve
2019	Antonioli et al. [2]	Standard	Pairing	●●◐○	✓	-	KNOB (MitM)
2020	Antonioli et al. [4]	Standard	Pairing	●●●○	✓	-	BIAS
2021	Tschirschnitz et al. [39]	Standard	Pairing	●●●○	✓	-	Method Confusion (MitM)
Attacks on BLE							
2016	Jasek et al. [23]	Standard	NA	◐○○○	x	-	Black Hat
2019	Seri et al. [36]	Impl.	NA	○◐◐○	NA	✓	Bleedingbit
2020	Zhang et al. [44]	Standard	Pairing	◐◐◐○	✓	-	MitM (SCO)
2020	Wu et al. [42]	Standard	Session	○○●○	✓	-	BLESA
2020	Garbelini et al. [17]	Impl.	Any	◐◐◐○	NA	-	SweynTooth fuzzer
Attacks on both BLE and BT							
2019	Ossmann et al. [30]	Standard	NA	◐○○○	x	-	Ubertooth sniffer
2020	Antonioli et al. [5]	Standard	Pairing	●●◐○	✓	-	Downgrade (MitM)
2021	**This work**	Standard	Any	●●●◐	✓	✓	

Table 3: Overview of recent attacks on Bluetooth and BLE. C = Data Confidentiality, I = Data Integrity, A = Device Authentication, K = Key disclosure. No (○) Partially (◐), Yes (●).

security boundary provides the same security guarantees in the same threat model. Currently, this is not the case for Bluetooth as CTKD uses BT and BLE pairings to cross the security boundary and pairing over BT is different than pairing over BLE.

Usability should not outweigh security. CTKD was introduced to improve Bluetooth's usability, but, in light of the presented attacks, the usability benefits are not balancing the security issues also introduced with CTKD. Indeed, it is paramount to weight security and usability before introducing a critical security feature, especially if it allows crossing a security boundary.

8 RELATED WORK

We summarize the positioning of our attacks compared to to related work in Table 3, and provide additional details on those attacks in the following. In general, the BLUR attacks are the first cross-transport attacks (targeting both BT and BLE), are standard-compliant (i.e., expected to work on any device that supports CTKD), can be executed outside the victims' initial pairing phase, provide comprehensive compromise of the security properties, break the most secure Bluetooth modes (secure connections), and provide persistent compromise of the victims.

The Bluetooth provides a royalty-free and widely-available cable replacement technology [18]. Bluetooth standard compliant attacks are particularly dangerous as all Bluetooth devices are affected, regardless of version numbers or implementation details. Such standard-compliant attacks have appeared since the first versions of Bluetooth [22, 27]. Standard-compliant attacks on BT include attacks on legacy pairing [37], secure simple pairing (SSP) [9, 19, 38], Bluetooth association [20, 39], key negotiation [2], and authentication procedures [4, 26, 40]. Standard-compliant attacks on BLE include attacks on legacy pairing [34], key negotiation [5], SSP [9, 44], reconnections [42], and GATT [23]. Compared to the mentioned attacks that target either BT or BLE, the BLUR attacks are the first standard-compliant attacks targeting the intersection between BT and BLE.

We have seen attacks targeting specific implementation flaws on BT [35] and BLE [17, 36]. As our BLUR attacks target the specification level, they are effective regardless of the implementation details. Several surveys on BT and BLE security were published [15, 29, 31] but neither of those surveys nor the Bluetooth standard considers CTKD as a threat. We here demonstrate that CTKD is a serious threat and must be included in the threat model.

Cross-transport attacks were exploited for proximity technologies using Bluetooth and Wi-FI. Two prominent examples are attacks on Apple ZeroConf [8] and Google Nearby Connections [3]. Our BLUR attacks are the first cross-transport attacks for BT and BLE.

The cryptographic primitives used by Bluetooth have been extensively analyzed. For example, the E_0 cipher used by BT was investigated [16] and it is considered relatively weak [31]. SAFER+, used for authentication, was analyzed as well [25]. BT and BLE "Secure Connections" use the AES-CCM authenticated-encryption cipher. AES-CCM was extensively analyzed [24, 33] and it is FIPS-compliant. Our BLUR attacks target key negotiation and not cryptographic primitives, and are effective even with perfectly secure cryptographic primitives.

9 CONCLUSION

In this work we examine CTKD, a usability feature in the Bluetooth standard that has, until now, not been scrutinized for security issues by the research community. We develop four attacks that take advantage of CTKD to exploit both BT and BLE. Our attacks are the first examples of cross-transport attacks on Bluetooth, they are standard-compliant, and effective against the most secure BT and BLE modes (i.e., Secure Connections and Secure Connections Only). Our attacks are the first ones that achieve a persistent compromise of the devices, i.e., it leaves the devices in a compromised state even when the attacker is no longer present. In contrast to other prior standard-compliant attacks (i.e., attacks that also are not targeting implementation bugs), our attacks are not limited to the pairing phase. That means we can execute the attack on any device at any time, without forcing a new pairing event.

With our BLUR attacks we reach four significant goals. We achieve impersonation and take-over for both the master and slave devices; man-in-the-middle on secure sessions in the most secure mode (Secure Connections); and establishing unintended sessions as an anonymous device. Collectively our attacks are called BLUR attacks as they blur the security boundary between BT and BLE.

To demonstrate the practicality of the BLUR attacks, we presented a low-cost implementation based on cheap readily available hardware (a laptop, and a Bluetooth development board) and open-source software (Linux, and internalblue). We also describe solutions to the main technical challenges we faced during development, including low-level modifications of a Bluetooth firmware.

We use our implementation to experimentally confirm that CTKD-compatible devices (using 10 unique Bluetooth chips) are vulnerable in practice. Our attacks are successful on all the devices we tested which shows that this is a serious problem in practice. We end the paper by discussing the feasibility of various low-cost, host-based countermeasures that prevent the attacks at the cost of some usability. We followed a responsible disclosure process and notified the Bluetooth SIG of our findings, resulting in CVE-2020-15802, and we intend to release our attack implementation as an open source project.

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